

NASA/TM—2001-211139



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Prepared for the
Seventh Ka-Band Utilization Conference
sponsored by the Istituto Internazionale delle Comunicazioni
Santa Margherita Ligure, Genoa, Italy, September 26–28, 2001

National Aeronautics and
Space Administration

Glenn Research Center

November 2001

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KA-BAND PHASED ARRAY SYSTEM CHARACTERIZATION

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Abstract—Phased Array Antennas (PAAs) using patch-radiating elements are projected to transmit data at rates several orders of magnitude higher than currently offered with reflector-based systems. However, there are a number of potential sources of degradation in the Bit Error Rate (BER) performance of the communications link that are unique to PAA-based links. Short spacing of radiating elements can induce mutual coupling between radiating elements, long spacing can induce grating lobes, modulo 2π phase errors can add to Inter Symbol Interference (ISI), phase shifters and power divider network introduce losses into the system. This paper describes efforts underway to test and evaluate the effects of the performance degrading features of phased-array antennas when used in a high data rate modulation link. The tests and evaluations described here uncover the interaction between the electrical characteristics of a PAA and the BER performance of a communication link.

1. Introduction

In future satellite communication systems, the demand for faster access and more information are expected to increase due to the continuous growth of the Internet and direct-to-user satellite requirements. Meeting these requirements will require multibeam satellite systems having an onboard active phased array antenna system. Phased Array Antenna based communications links are anticipated to deliver high data rates without the risk of single point failure gimbaled motors used in reflector-based systems.

Phased array antennas contain a multitude of radiating elements, typically arranged in a rectangular or triangular tessellation. Beams are formed by electrically adjusting the relative phase of the radiating elements using ferrite or semiconductor devices [1]. Phased array antennas have been developed mainly for radar applications but are being used more now for space-based communications applications due to their advantages in scanning, reconfigurability, weight and power.

In PAA-based links, BER-limiting reductions in the demodulated E_b/N_0 are caused by mutual coupling between elements and power losses generated by grating lobes. Mutual coupling can also lead to blind angles. Phased array antennas also introduce additional Inter-Symbol Interference (ISI) into the channel due to delay across the aperture and 2π limitations on phase shifters. These effects become particularly significant given the high data rate anticipated with PAA communications systems. Further complications unique to PAA-based systems include phase-shifter transients and thermal distortions.

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The RF output power of the transponder will need to be on the order of several hundred watts to enable easy access small and low cost earth terminals. Generally, the power efficiency, undesirable Inter-Modulation (IM) distortions of the High Power Amplifiers (HPAs) [2], undesirable transient effects of the phase shifters, limited phase shifting to modulo 2π and grating lobes will limit the performance of phased array antennas. Array system characterization is a special battery of specialized tests that includes modulation and antenna correlations under the array dynamic operating conditions.

This paper describes a number of measurement techniques that, collectively, characterize the performance of phased array antennas. With an understanding of PAA links, techniques can be developed to mitigate the effects of high interaction between modulation rates and array RF characteristics.

2. Transmit Array System Antenna Characterizations

To investigate the relationship of data rates and array RF characteristics, several tests were conducted. The co-polarized and cross-polarized antenna patterns, effective isotropic radiated power (EIRP) and BER as a function of scanning angle are measured to define the static characteristics of the phased array. Secondly, the array transient and intermodulation characteristics are tested for all scanning angles by dynamically changing the beam direction and measuring the burst error rates. In the future, the array will be tested in a dynamic environment where the BER will be recorded as function of time and scanning angle.

2.1 Transmit Array Antenna Pattern and EIRP Test Description

The array antenna pattern and EIRP are tested in far-field anechoic chamber described in Figure 1. The patterns are measured by setting the beam direction and rotating the array pedestal mechanically in azimuth and elevation. The antenna is operated in continuous wave mode and tested at three different frequencies; at the low, center and high end of the band.

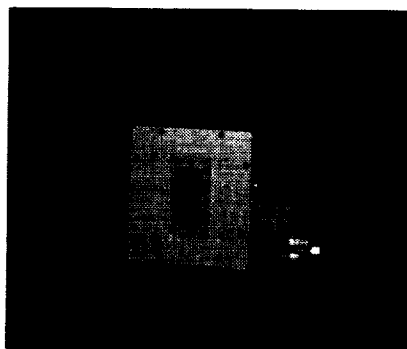


Figure 1. 30 GHz transmit 8 x 4 elements phased array antenna system in the anechoic chamber.

For an antenna pattern test, the array antenna is placed in a far-field anechoic chamber. The EIRP test measures the sidelobe level envelope and grating lobe positions. The EIRP is measured for all scanning angles by comparing the power generated by the transmit phased array with the received power generated at the same distance by a standard gain horn antenna where the gain and input power are well know.

An example of the antenna pattern test for the 30 GHz, 32-element phased arrays depicted in Figure 1, is illustrated in Figure 2. The peak EIRP was measured at 130 watts.

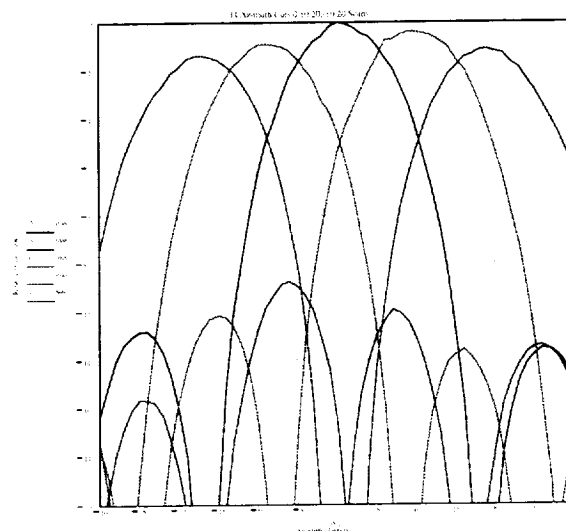


Figure 2. H-Plane antenna patterns as function scan angle.

2.2 Transmit Array BER Test Description

The BER of the phased array system can be measured as a function of E_b/N_0 by inserting a controlled noise signal into the received signal prior to the signal entering the demodulator. This noise signal can be varied in order to create a range of E_b/N_0 values. The results should agree with the theoretical system curve for the type of modulation used with a slight offset due to modem implementation loss.

A block diagram for a BER test system is shown in Figure 3. In this system, a BER test set estimates the bit error rate of the system. An experiment PC queries the modem and test set and records the E_b/N_0 and the corresponding BER. The test configuration comprised of BPSK modulation and a 1.54 Mbps information data rate with no coding or scrambling of the data. The modem used was a COMSTREAM modem which measured the E_b/N_0 internally.

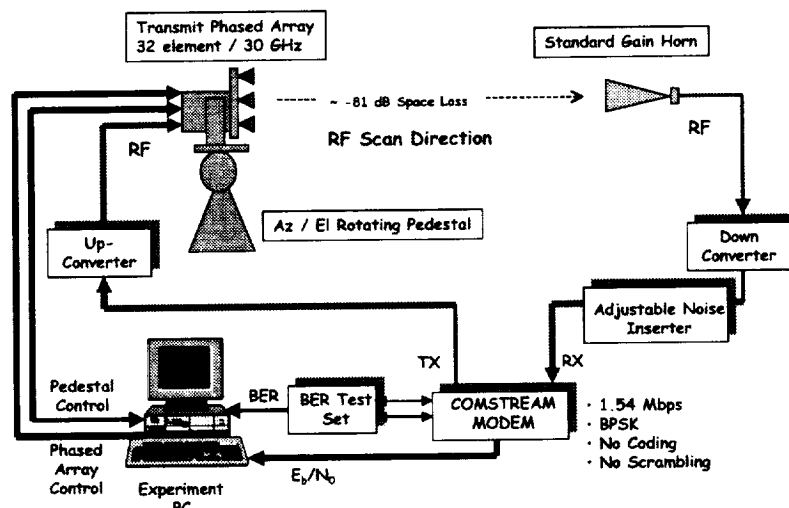


Figure 3. BER system test block diagram.

To perform this test, the phased array is scanned to the test angle and then the pedestal is moved in the reverse direction so that the primary beam from the phased array remains focused on the standard gain horn antenna. With no additional noise, the bit error results are reset to zero and a known test pattern of bits is sent through the system. These are compared to the received bit pattern and a BER is measured. This test is conducted for 3 minutes. After three minutes of test, the BER and E_b/N_0 are recorded by the experiment PC. The test continues by adding noise to the channel sufficient to decrease the E_b/N_0 by approximately 1 dB and another three minutes of data are collected for BER estimation. This process is repeated until the test set cannot maintain pattern synchronization. This test is repeated for each desired scan angle. By rotating the phased array 90 degrees on the pedestal, the same tests were conducted in the H-plane.

Figure 4 shows the measured BER as function of scanning angle. The results show some modem implementation loss. Effects of ISI are not observed due to high ratio of carrier frequency to data rate.

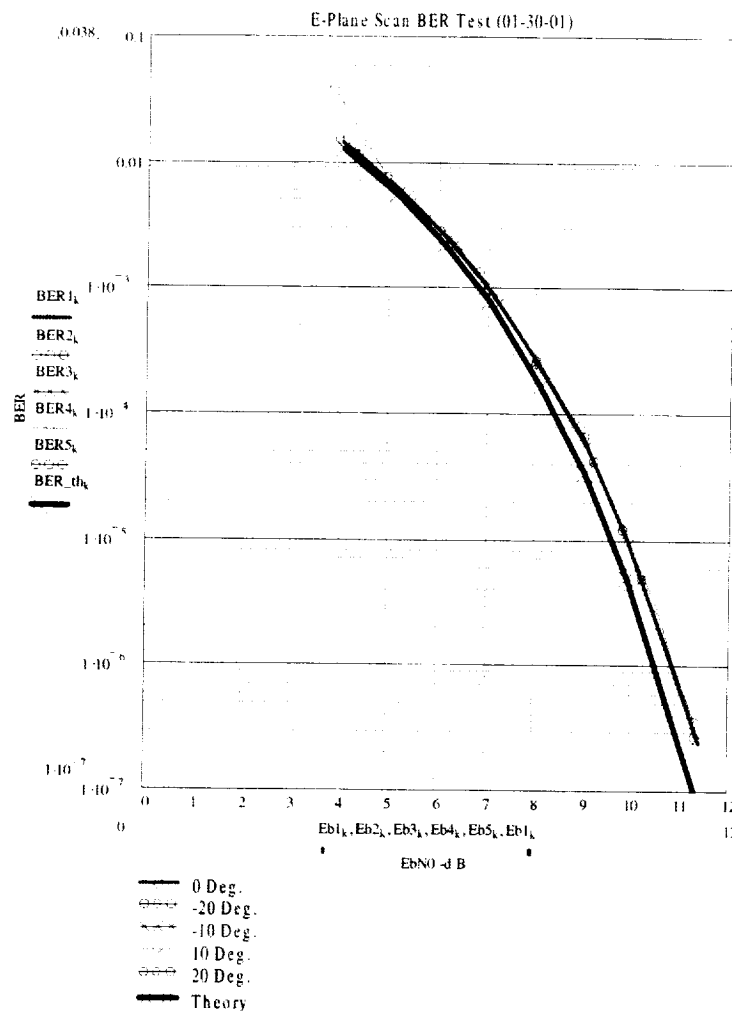


Figure 4. E-Plane scans and bit-error-rate measurements.

2.3 Transmit Array Transient Test Description

When the beam of a PAA antenna is switched from one pointing direction to another, transient effects on the communications channel are observed. Such transients can be attributed to either electrical 'ringing' of the antennas phase shifters or are due to the non-simultaneous switching of the phase shifters. In some beamformers, switching of the phase shifters is designed to occur in a 'ripple' manner in which only a few phase shifters are changed at a time. This design is, apparently, intended to minimize the effect of beam switching. Apart from the immediate effect of inducing errors in the detection of transmitted symbols occurring during a beam-switch transient, a more serious effect of beam-switch transients is the potential loss of synchronization with the carrier or frame.

Synchronization loss requires re-acquisition and thus induces a burst of symbol errors. It is therefore possible for a relatively short beam-switch transient to cause extended bursts of errors, which in turn, increases composite BER. The lower the spacecraft altitude, the more beam switching occurs and the shorter the flyover time. Thus, the potential for synchronization-loss induced burst errors to contribute to system BER increases with decreasing spacecraft altitude. Furthermore, note that the beam switch rate is highest at spacecraft zenith. Thus, the potential for beam-switching induced errors appears to be greatest when slant range is the least and, by extension, E_b/N_0 is the greatest. The objective of transient testing is to assess the extent of this effect on fully integrated PAA-based communications links.

The block diagram that illustrates the transient diagnostic test is shown in Figure 5. In this test a continuous wave RF source is used as input to the transmit PAA. A step response is measured by switching the pointing direction of the beam through the PAA controller inside the experiment PC. The received signal from the standard gain horn is downconverted to a frequency near DC so as to place the spectrum of the transient within the passband of a data acquisition card in the experiment PC. Test operation consists of commanding a switch in the pointing location of the beam of the transmit PAA and, soon after, latching data into the data acquisition card. Extraction of a true 'step response' is accomplished by further

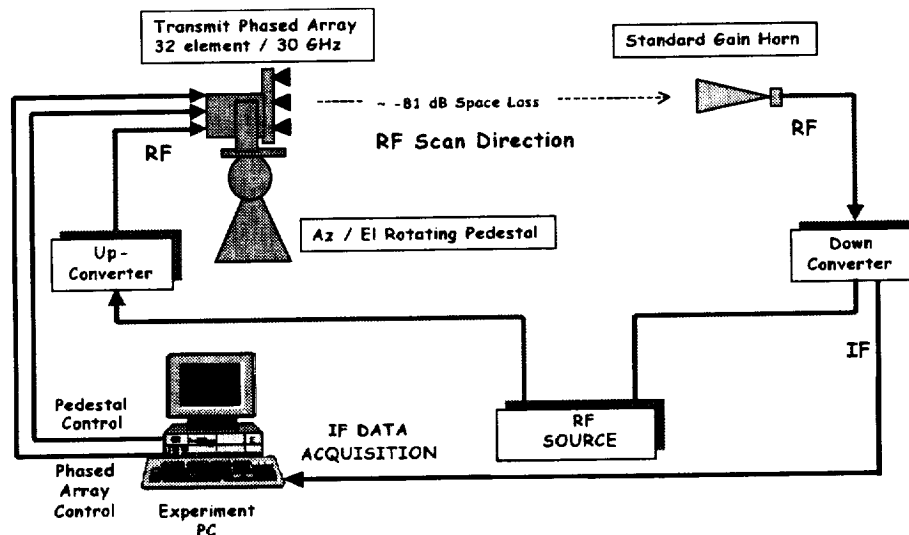


Figure 5. Transient diagnostic system test block diagram.

downconversion of the time samples of the IF data once it has been digitized. Step response duration, overshoot and other relevant parameters can be estimated from the latched data. Small changes in beam location are used to simulate transient effects under normal operating conditions. As transient duration and magnitude is expected to vary with magnitude of scan angle change (more shifters to shift, larger changes in power level), large changes in beam pointing angle are used to assess worst-case effects.

2.4 Intermodulation Test Description

The Inter-Modulation (IM) test is also performed in the far field. The objective of this test is to show that the received carrier and IM power patterns have almost the same shape. There should be some relationship between the amplitude and phase of the IM and those of the carriers. To maintain the high carrier power to IM distortion power ratio (C/IM), the Output Back Off (OBO) level must be several dB lower than the output saturation point. In the near-saturated region, power efficiency decreases by 5% for every 1 dB increase in the OBO level. The power efficiency of current onboard HPAs, which is normally a high 40% or more, decreases to about 25% at the operation. This is a serious problem because of the poor power-generating and heat-shedding abilities of satellites. It is important to improve C/IM of an HPA used in the near-saturated region.

2.5 Dynamical Array Testing of BER

In the future, static BER testing will be supplanted with dynamic BER testing. The purpose of dynamical BER testing is to estimate link performance under the operational conditions of a highly dynamic LEO-to-ground-station communications link. With the dynamical BER testing, LEO satellite flyover conditions will be simulated in real time so as to replicate both the distribution of satellite and ground station look angles, as well as the temporal progressions of link geometry. The resulting estimates of BER will reflect an aggregate error rate consisting of both aleatory errors associated with thermal noise induced symbol errors together with the more systematic errors associated with time-varying link margins.

In addition to the system described for the static BER testing, dynamical BER testing will include facilities to generate geometric/temporal flyover scenarios. These scenarios will be used to simultaneously control the electronic beamformer(s) of the phased array antennas together with the pedestal controllers to simulate the geometric relationship between transmitter and receiver in "real time." Effects of time varying slant range may be partially included in the simulation by incorporating time varying attenuation. Incorporating propagation delay is not being considered as part of the testing system. Dynamical BER testing will be performed over a variety of modulation rates, types and coding types. Dynamical BER testing will thus characterize the sum of most link effects that are present in the PAA-based link as a function of data rates and scanning dynamics.

3. Phased Array BER Modeling

Many authors have modeled phased array antennas for the past 50 years [3]. With the advent of computer programs like MATLAB and SIMULINK we can now easily model the array radio frequencies and modulation interactions. The simulation can be custom fitted to a specific modulator/demodulator combination. The array RF simulation is well-understood and very easily implemented using MATLAB. Figure 6 shows a simple implementation of a phased array and Binary Phased Shift Keying (BPSK) demodulator.

Figure 7 shows the simulated BER curve for different scan angles. Notice that ISI due to the phased shifter 2π limitation is very noticeable as the scan angle is increased.

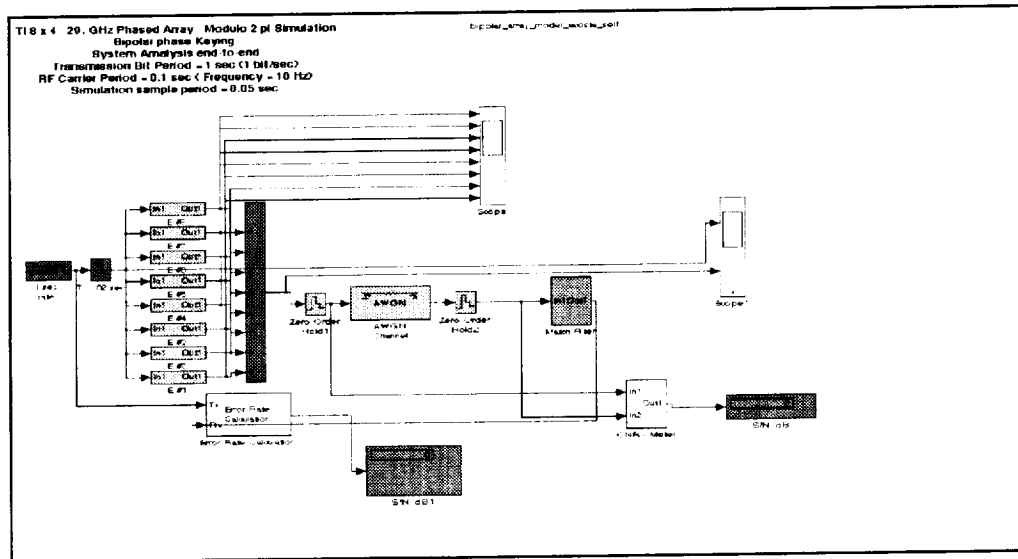


Figure 6. MATLAB SIMULINK model of PAA with BPSK modem.

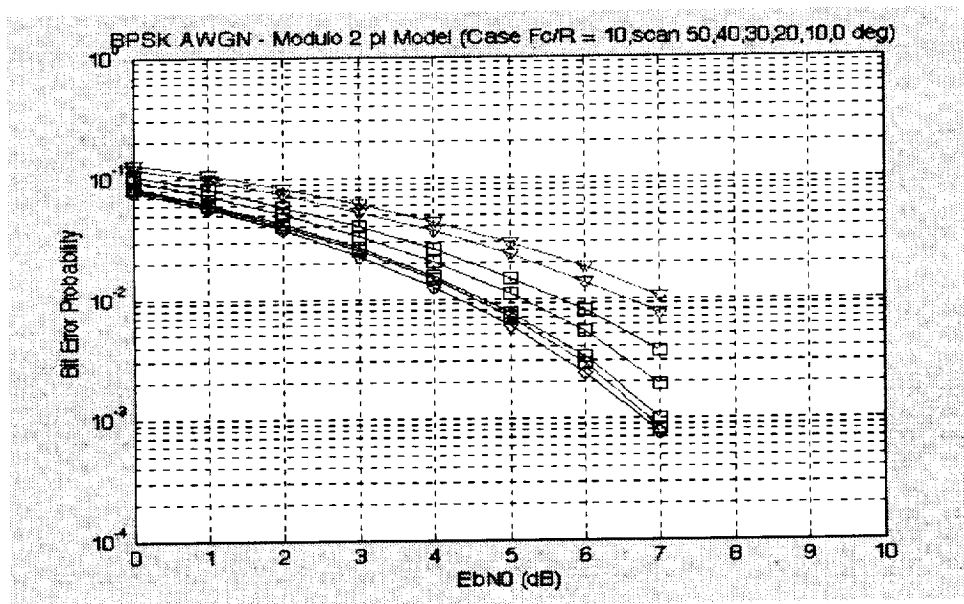


Figure 7. Simulated BER results for the 32-element phased array.

4. Summary

Phased array antennas provide several advantages over gimbaled reflector antenna systems for delivering large amounts of data from LEO satellites. The experiments presented in this paper provide future antenna system engineers with a good understanding of the interaction between radio frequency and high rate modulation for a given array design. Compensating techniques can be provided to mitigate or minimize degradations of array antennas. It is expected that phased array antenna will become the primary technology for LEO satellite data communications.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE November 2001		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE Ka-Band Phased Array System Characterization			5. FUNDING NUMBERS WU-322-10-2C-00	
6. AUTHOR(S) R. Acosta, S. Johnson, O. Sands, and K. Lambert				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-12994	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-2001-211139	
11. SUPPLEMENTARY NOTES Prepared for the Seventh Ka-Band Utilization Conference sponsored by the Istituto Internazionale delle Comunicazioni, Santa Margherita Ligure, Genoa, Italy, September 26-28, 2001. R. Acosta, S. Johnson, and O. Sands, NASA Glenn Research Center; and K. Lambert, Analex Corporation, 3001 Aerospace Parkway, Brook Park, Ohio 44142. Responsible person, R. Acosta, organization code 6120, 216-433-6640.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Categories: 32 and 66 Available electronically at http://gltrs.grc.nasa.gov/GLTRS This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Phased Array Antennas (PAAs) using patch-radiating elements are projected to transmit data at rates several orders of magnitude higher than currently offered with reflector-based systems. However, there are a number of potential sources of degradation in the Bit Error Rate (BER) performance of the communications link that are unique to PAA-based links. Short spacing of radiating elements can induce mutual coupling between radiating elements, long spacing can induce grating lobes, modulo 2π phase errors can add to Inter Symbol Interference (ISI), phase shifters and power divider network introduce losses into the system. This paper describes efforts underway to test and evaluate the effects of the performance degrading features of phased-array antennas when used in a high data rate modulation link. The tests and evaluations described here uncover the interaction between the electrical characteristics of a PAA and the BER performance of a communication link.				
14. SUBJECT TERMS Antenna; Phased arrays; System analysis; Ka-band antennas			15. NUMBER OF PAGES 14	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

